Proposal to United States Department of the Interior National Parks Service

I. INTRODUCTION

a. Title

Measuring present-day mountain growth in Olympic National Park

b. Date of proposal

Saturday, September 18, 2004

c. Investigators:

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d. Table of contents

e. Abstract

How are mountains able to grow and sustain their topography given the constant erosion of rivers, glaciers, and landsliding? What are the relationships between tectonic uplift, erosion, and climate? Recent studies from Olympic National Park have made new progress on these old questions. This work started with thermochronologic measurements, which provide isotopic ages for erosional history of the Olympic Mountains on a timescale of millions of years. The conclusion was that the range has slow erosion rates near the coast, but increases to high rates, about 1 km per million year, in the core of the range. In other words, tectonic uplift must be active to sustain the topography of the range, otherwise it would be eroded away within several million years. We have used the Clearwater River, located on the west side of the range, to measure rates of tectonic uplift on the time scale of the last 100 thousand years. The conclusion is

that uplift and erosion have been in balance for 7 million years or more. The Olympic Mountains are now widely recognized as a steady state mountain range, which means that they have been able to hold their own relative to erosion by rivers, glaciers and landslides.

Our goal now is to determine the pattern of horizontal and vertical motions of the landscape in the Olympic Mountains on the time scale of years. This study will allow us to understand how long-term uplift that is responsible for sustaining the Olympic Mountains relates to short-term cycles of uplift and subsidence caused by earthquakes on the Cascadia subduction zone, which underlies the entire Park. In the past, this issue could not have been addressed because the rates with which mountains change their physical shape are extremely slow, on the order of 1 mm per year. New satellite-based technology now provides the ability to accurately measure modern rates of mountain formation. Olympic National Park is an ideal natural laboratory for this study given our detailed understanding of the geologic evolution of the range, the exceptional sky-visibility afforded by the high peaks (which is needed for the satellite-based measurements), and the importance of the area to understand the seismic hazards of the Cascadia subduction zone. This document outlines our request for permission from the Park Service to install Global Positioning System (GPS) receivers within the park to measure the rates of mountain formation within the park. Many of the stations could be operated in a real-time fashion which would allow a unique opportunity for park visitors to directly see tectonic movements within the range as they occur on a day by day basis.

II. OVERVIEW

a. Statement of issue

The Olympic mountains are situated above the Cascadia subduction zone (Figure 1), where the oceanic Juan de Fuca plate plunges beneath the North America continent at a rate of about 36 millimeters every year (mm/yr). As the Juan de Fuca plate descends, the blanket of sediments accumulated on the ocean floor is scraped off and transferred to the North America continent forming an “accretionary wedge” (Figure 1B). This process of accretion, which transforms the ocean bottom sediments into sedimentary rocks as it accumulates along the edge of the continent, is thought to be responsible for the high topography of the Olympic National Park.

To-date, the only constraints we have on the rates of uplift within the Olympic Mountains have been inferred from geologic studies. Although extremely valuable, these data are limited in that they represent average rates over very long time-scales, which may or may not reflect contemporary rates. New satellite-based technology now allows us to directly measure contemporary motions of Earth’s surface with extremely high precision, as demonstrated at many places around the world, where small motions associated with active fault zones and volcanoes have been determined with accuracy better than a fraction of millimeter per year accuracy. With this new technology we can, for the first time, answer one of the long-standing questions in the natural sciences: how do mountains grow?

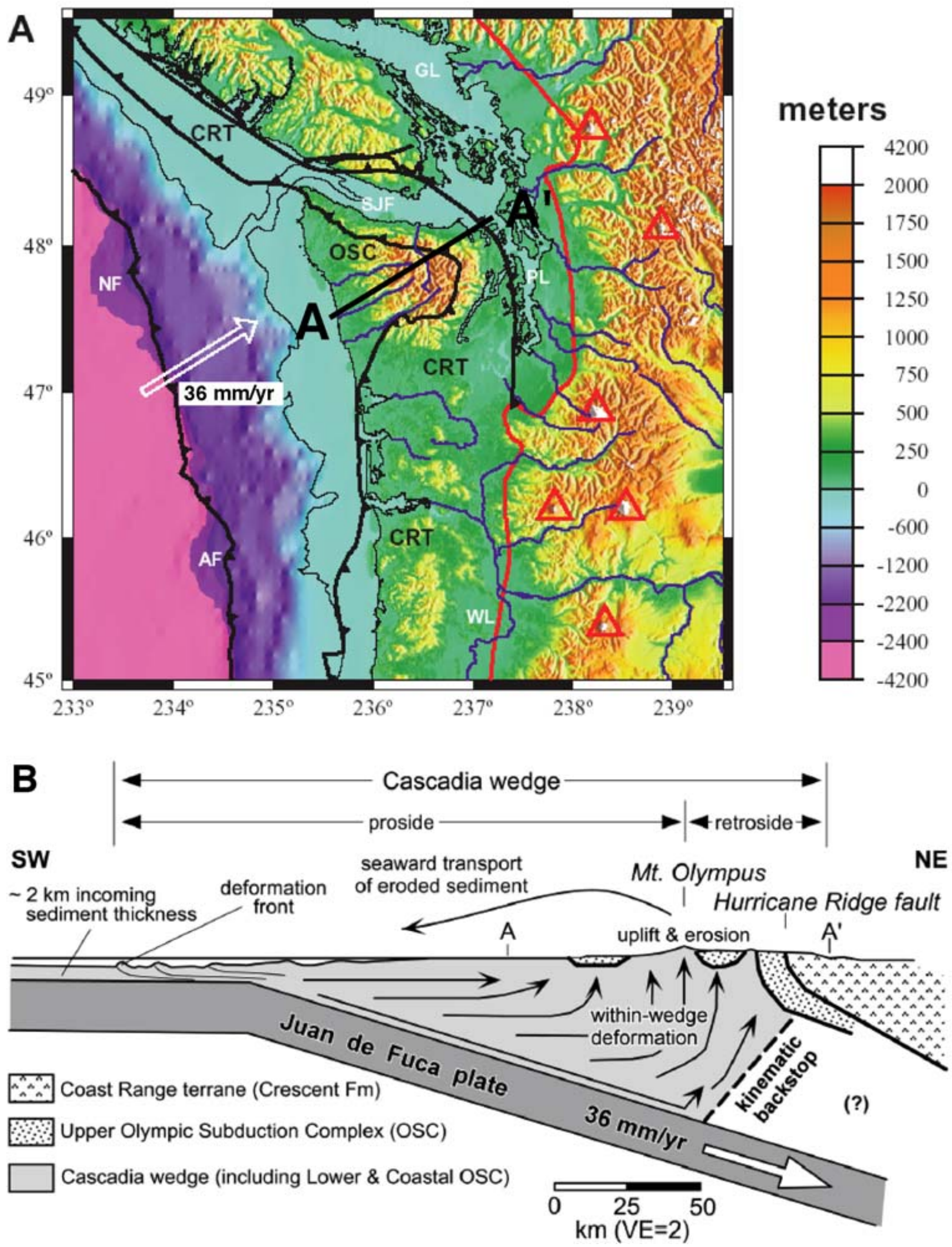

Figure 1. Tectonic setting of the Cascadia subduction zone beneath Olympic National Park. (A) Shaded relief map. Solid black lines mark major faults. The solid red line marks the western limit of Cascadia volcanism. Red triangles show locations of volcanoes. Blue lines show major rivers. (B) Schematic section (A-A' from Figure 1A above) illustrates the relationship of the Olympic Mountains to the Cascadia subduction system. The arrows in the Cascadia wedge conceptually illustrate the accretion model of Brandon et al. (1998) and Pazzaglia and Brandon (2001), wherein sedimentary cover from the ocean floor is first accreted and then moves over 150 km through the Cascadia wedge. The accreted sediments are converted to rock by high pressures and temperatures, and then are gradually exhumed by erosion in the Olympic Mountains, which returns the rocks as sediment back to the seafloor. White arrows show the motion of Juan De Fuca plate with respect to the North America continent. CRT = Coast Range Terrane, OSC = Olympic Subduction Complex. Figures modified from Brandon et al., 1998 and Pazzaglia and Brandon, 2001.

b. Literature summary

We summarize here previous studies in Olympic National Park, starting with geodetic studies. The term "geodetic" refers to the measurement of the shape of the global and the position of points on its surface. As used here, we are referring to the motion of geographic points at the earth's on the time frame of years. Savage et al. (1991) report on geodetic data collected by the United States Geological Survey (USGS) over the period of 1982 to 1990 in Olympic National Park. The USGS network, referred to as the Olympic Trilateration Network, remains in place within the Park as an active part of the national geodetic control network. It consists of geodetic markers located at Hurricane Ridge, Blue mountain, Cameron Glacier Cirque, Mount Dana, Dodger Point, Eagle Peak, Gray Wolf Ridge, and Mount Carrie. Savage et al. (1991) used the data collected from this network to estimate the contemporary rate of spatially-averaged horizontal deformation within the eastern Olympic Mountains. Although the USGS results were limited to horizontal motions and spatial averages by the terrestrial-based technology available at the time, their work provided the first tantalizing glimpse of the rates and styles of rock deformation within Olympic National Park. Savage et al. (1991) foresaw the importance of the then-new satellite-based Global Positioning System (GPS): "Future measurements of deformation along the Cascadia subduction zone are likely to depend upon Global Positioning System surveys. These surveys have the capability of measuring the relative position of two stations with high precision even though the stations are not inter-visible." In fact, in 1996, the USGS re-surveyed the Olympic network using GPS (Jerry Svarc, personal communication). Two of the eight monuments were also surveyed in 2002 with GPS. Future USGS GPS surveys of the entire Olympic Trilateration Network are uncertain.

Brandon et al. (1998) and Batt et al. (2001) used radioactive isotopic dating methods (dating of the mineral apatite using fission tracks and He produced by natural decay of uranium and thorium) to determine the thermal histories of the rocks comprising the Olympic Mountains. The ages provide information about the rate at which rocks cooled through time, which can be used to estimate the erosion rates responsible for exhuming these rocks from great depth within the accretionary wedge over time-scales of millions of years. They found that long-term erosion rates over the past several million years ranged from near zero around the periphery of the mountain range, to as high as 1.2 mm/yr (equivalently 1.2 kilometers per million years) near Mt Olympus (Figure 2). The central massif to the east of Mt Olympus, where the USGS Trilateration Network is located, is eroding at intermediate rates between about 0.5 and 0.7 mm/yr.

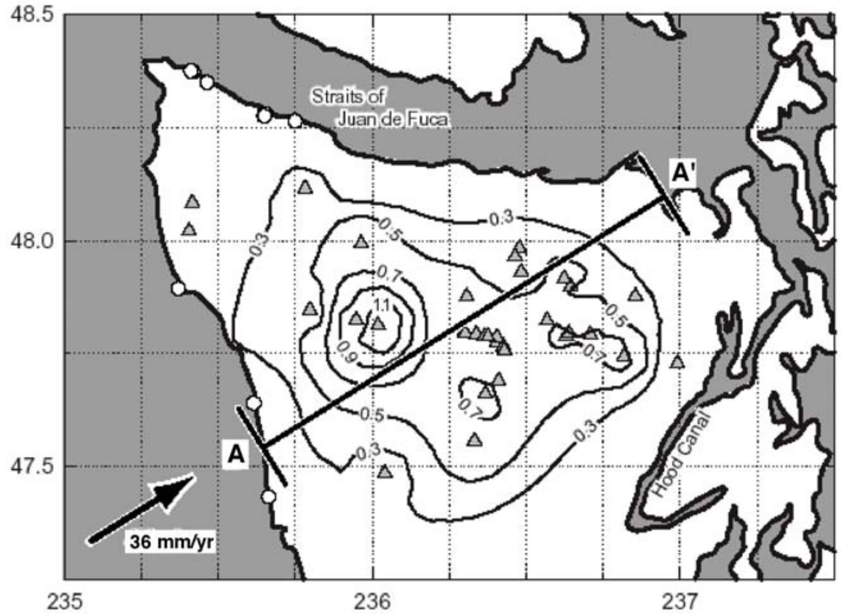

Figure 2. Contour map showing long-term exhumation rates in the Olympic Peninsula. Triangles show the locations of the rock samples that were used to determine the rates. Figure modified from Brandon et al., 1998.

Pazzaglia and Brandon (2001) studied the abandoned segments of the river channel located on the hillslopes above the modern Clearwater River to measure rates of tectonic uplift on time-scales of hundreds of thousands of years. The interesting conclusion is the rates of uplift are similar to the rates of erosion. Rate agreement across such disparate time-scales suggests that uplift is steady through time, with uplift balanced by an equivalent erosion. Batt et al. (2001) used a more comprehensive 2-dimensional thermal and kinematic model to analyze the isotopic age data. They found that the model indicated a steady balance between uplift and erosion over a time frame of 14 million years. Pazzaglia and Brandon developed a theoretical model for the formation of the Olympic mountains relating the slow, large-scale, primarily horizontal, relative motion of the Juan de Fuca and North America plates to the uplift within the Olympic mountains (Figure 1B). Their model can be used to predict contemporary rates of horizontal motion and mountain uplift. The experiment that we propose would provide the first test of their model at short time-scales.

These previous studies have been investigating processes of mountain formation at time scales much longer than the recurrence time for major earthquakes, which is about 100 to 1000 years. Studies of coastal geology along the Pacific coast of Oregon, Washington and Vancouver Island have demonstrated that the stick-slip motion associated with earthquakes on the Cascadia subduction zone causes a cycle of uplift and subsidence of the coast, with the earthquake itself marked by rapid coastal subsidence (Atwater, 1987, 1996; Leonard et al., 2004). This motion has a magnitude of 1 to 2 m and a recurrence time of about 500 years (Figure 3). The jerky motion is cyclic and averages to zero, so it is not seen in long-term studies of uplift, but it would be significant for our geodetic study. For instance, Pazzaglia and Brandon (2001) estimate that about 20% to 35% of the geodetically measured horizontal strain in the Olympic Peninsula is associated with long-term growth of the Olympics, whereas the remaining strain is associated with stick-slip motion on the seismically active Cascadia subduction zone. One crucial question relevant to both earthquake hazards mitigation and our knowledge of mountain building processes is thus how much of the motion between earthquake events is due to this periodic bending (Figure 3), and how much is due to the accretion of sedimentary material (Figure 1B)? The geodetic experiment that we propose is designed to answer this important question.

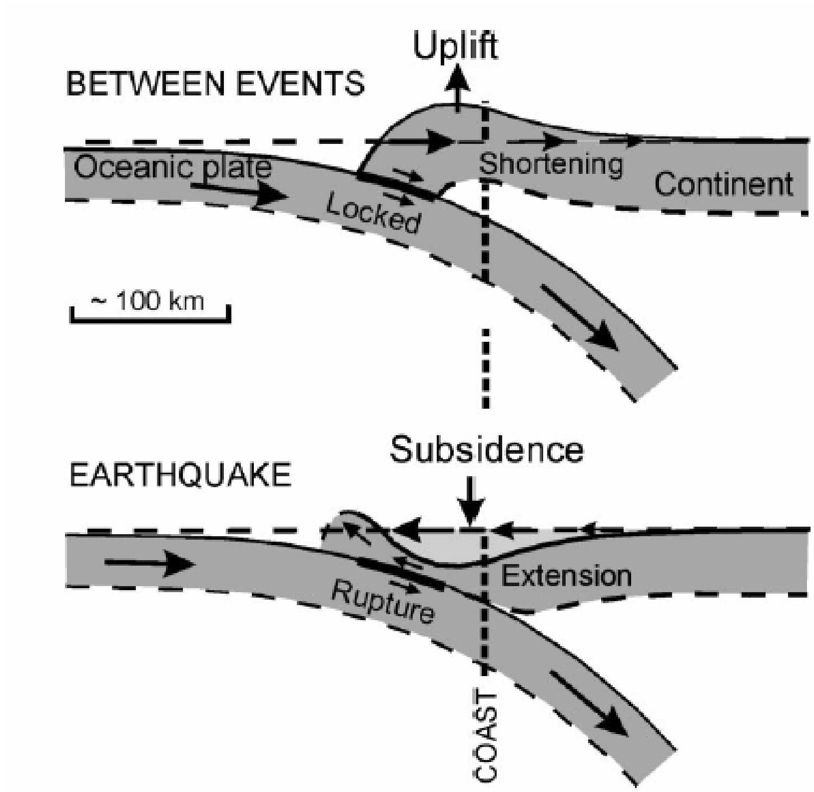

Figure 3. A conceptual model from Leonard et al. (2004) for the earthquake cycle of strain accumulation and release on the Cascadia subduction zone beneath Olympic National Park. As the oceanic Juan de Fuca plate converges on the North America continent, including the accretionay wedge, frictional resistance along the contact boundary between the two regions causes the rocks of the continent to bend. As the Juan de Fuca plate continues to move landward, stress builds on this interface. Bending of the continental material becomes more pronounced until finally the frictional strength of the interface is exceeded, at which point the rocks rebound into a less strained shape, resulting in a rupture along the interface, large-scale subsidence near the coast, and the generation of great earthquakes.

Recent GPS studies in southern Vancouver Island and western Washington State (Dragert et al., 2001; Thatcher, 2001; Miller et al., 2002; Rogers and Dragert, 2003) have shown that the subduction zone has pulses of motion that occur on the time frame of several months, which is much faster than the recurrence time for major earthquake. Dragert et al. (2001) observed a sudden shift in the horizontal motions of 7 contiguous GPS sites in the Pacific Northwest region (Figure 4). The sense of motion was found to be opposite of the steady-state motions attributed to the convergence of the oceanic Juan de Fuca plate and the North America continent. The time at which this change in motion was observed changed systematically, beginning earliest in the southernmost GPS stations and moving north at a rate about 6 km per day. These GPS observations led to the realization that the Cascadia subduction zone experiences silent earthquakes, that is, ruptures on the subduction interface that do not produce the violent shaking which characterize typical earthquakes. Subsequent analyses of GPS data from other parts of the Cascadia margin revealed that silent events occur in this subduction zone with regularity and that these events are correlated with periodic increases in apparent noise in seismograms from the region for which we previously had no explanation (Figure 5; Rogers and Dragert, 2003). These slow ruptures appear to nucleate beneath Olympic National Park. *If so, Olympic National Park will likely prove to be the best location from which to detect and monitor Cascadia's silent earthquakes*. Because these silent rupture events provide information about the frictional behavior and geometry of the subduction interface at depth, they may hold the key to disentangling the deformations associated with the subduction earthquake cycle (Figure 3) and sediment accumulation and mountain growth in the accretionary wedge (Figure 1B).

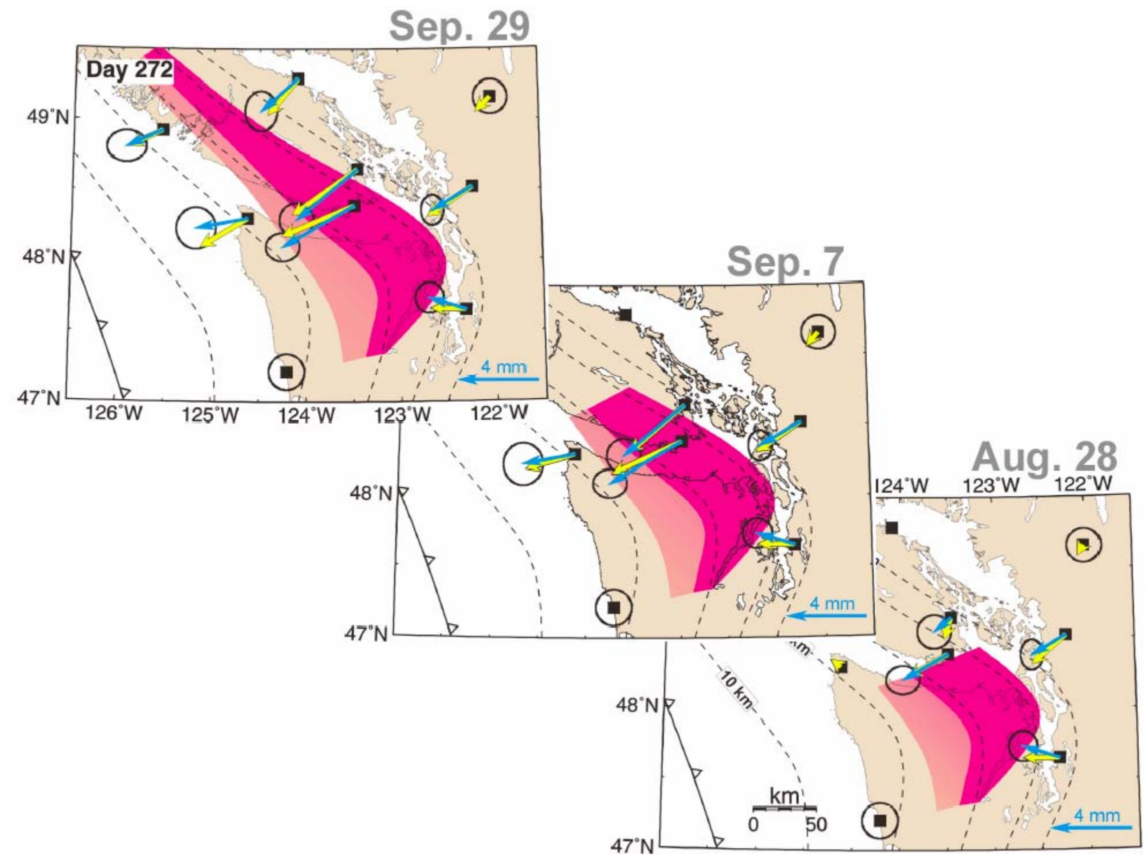

Figure 4. A model for the 1999 "silent" earthquake on the Cascadia subduction interface. Rupture occurred on the lower part of the subduction interface for a period of 35 days without producing the violent ground shaking characteristic of most earthquakes. Dashed lines represent depth contours of the subduction interface. Dark shading shows the part of the subduction interface that ruptured the most during this event. The lighter shading shows a region across which rupture tapered from zero at shallowest depth to the full amount. Only the lowermost regions of the interface appear to rupture in this relatively slow, aseismic fashion. The three panels of this figure show snapshots of the rupture at different times. Rupture began in the vicinity of the Olympic Peninsula in late August, then propagated to the north along the interface. Arrows show the surface deformation associated with this earthquake: blue = observed displacements with black ellipses showing 95% confidence regions, yellow = model predictions. Olympic National Park is an ideal location from which to observe slow

ground motions associated with Cascadia's silent earthquakes. Silent events may in fact be the key to disentangling strains associated with mountain building and earthquake generation processes. Figure modified from Dragert et al., 2001.

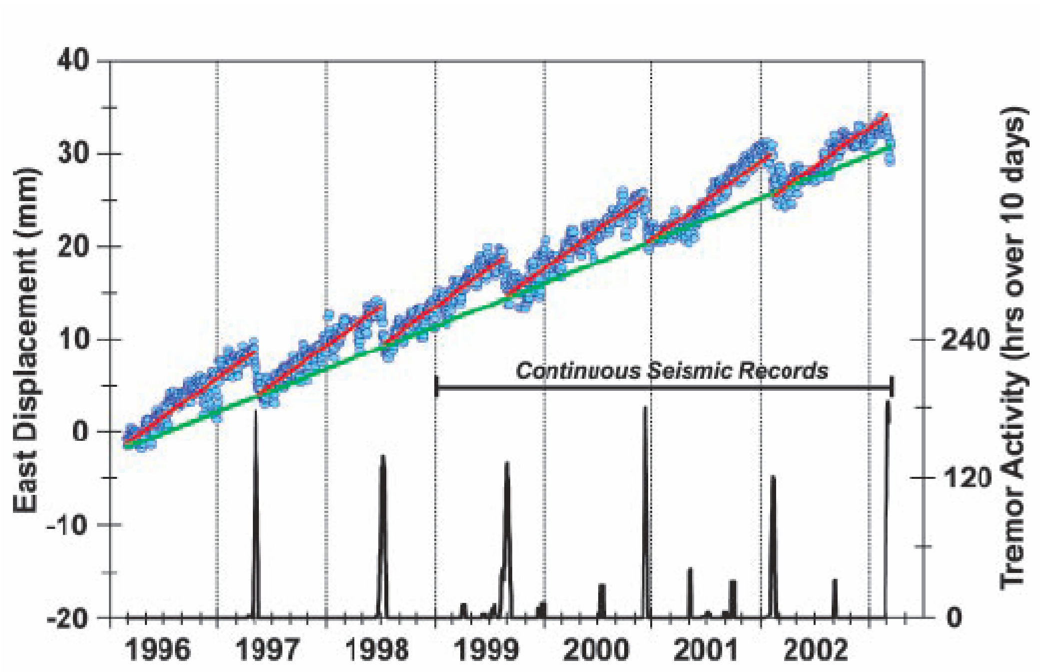

Figure 5. GPS position estimates as a function of time (blue dots), models for site motion (red and green), and seismic tremor (spikes represent the number of hours of increased seismic "noise" observed on seismograms over the Cascadia area in a 10 day time-window) illustrating the periodic nature of silent events on the Cascadia subduction interface. Silent events occur once every 1.0 to 1.5 years. Each silent event relieves stress buildup on the lowermost part of the interface, but increases stress on the uppermost part of the interface, potentially bringing the upper region closer to catastrophic failure.

c. Scope of study

The goal of our proposed investigation is to determine the rates and patterns of contemporary deformation of the Cascadia accretionary wedge within Olympic National Park. Our proposed scientific experiment would involve the following two phases: (1) construction of a set of seven modern geodetic markers collocated with existing sites of the USGS Trilateration Network, and (2) annual geodetic measurements of the precise positions of these markers. We describe these phases and their impacts on the Park in detail below.

We also seek permits for the construction of two continuous GPS reference stations, which would become part of the National Science Foundation's Plate Boundary Observatory Facility. We provide a description of the objectives of NSF's Plate Boundary Observatory and corresponding Earthscope Science Program, and the requirements and impacts on park resources of these proposed stations below.

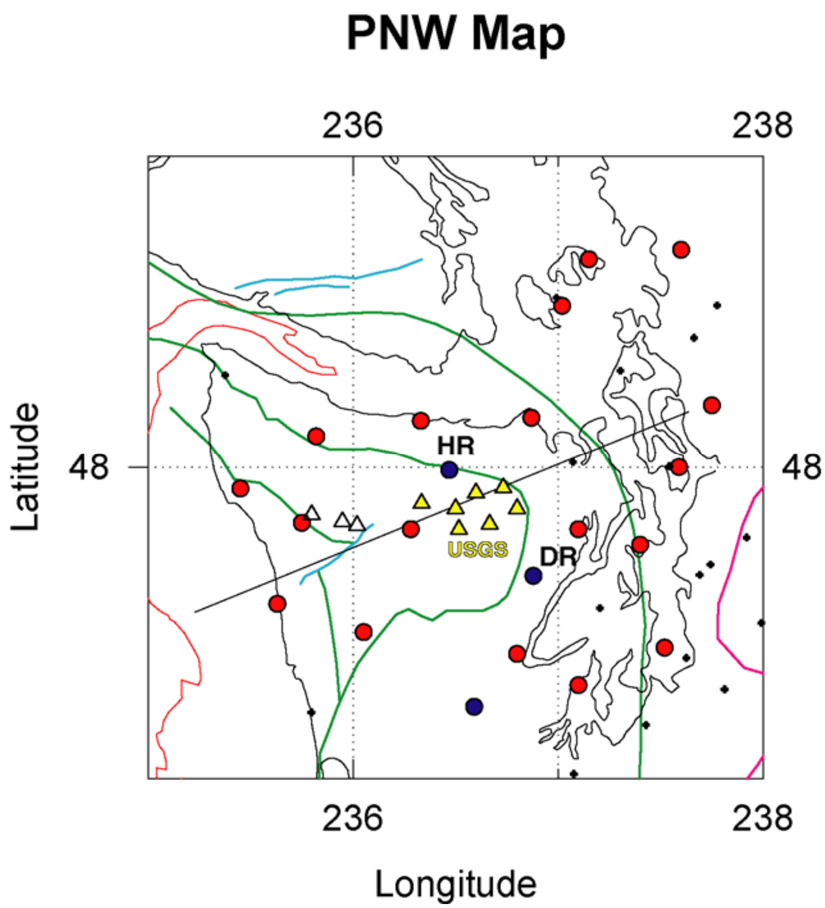

Figure 6. Proposed GPS sites in the Olympic National Park. Blue circles labeled HR and DR represent proposed PBO reference stations at Hurricane Ridge Visitor Center, and Dosewallips Ranger Station respectively. Yellow triangles show seven sites of the USGS's Olympic Trilateration Network at which we propose to add new, small, modern, high-stability GPS markers for measurement of very small ground motions. Other dots (red and blue) represent sites of the new PBO network. The red dot near Mt Olympus represents an existing continuous GPS reference station (SC03), which may be adopted by PBO. Although our experiment will make use of the important data collected by this station, it is not part of this proposal. Crosses show the locations of existing stations of the PANGA network. The stations that we propose in Olympic National Park would fill an important hole in the GPS coverage in the broader region and would allow us to address many outstanding questions pertaining to the formation of the mountain range that would not otherwise be addressed.

Phase 1: Modern survey network installation

We propose to complement the USGS Trilateration Network with modern high-stability geodetic markers at seven of the USGS sites: Blue Mountain, Cameron Glacier Cirque, Mount Dana, Dodger Point, Eagle Peak, Gray Wolf Ridge, and Mount Carrie (Figure 6). Installation of each marker will require short visits by two or three people to construct the new markers. Our target for installation is July 2005. Markers will be anchored into bedrock by drilling a small hole, approximately 100 cm deep and 3 cm diameter, into the ground, and inserting and affixing with epoxy a stainless steel pin. The monument design is very similar to the existing USGS markers, except that our markers are equipped with threaded holes, which provide the capability of precisely attaching GPS antennas via specially fitted, fixed-height (15 cm) high antenna adaptors. When not in use, these threaded holes will be closed with smooth topped caps. The markers, including the caps, have a total diameter of 10 centimeters, and will be set in the rock flush with the surface to minimize visual impact. We anticipate that installation of each monument will take less than an hour. We thus expect this phase of the experiment to have minimal impact on park visitors. Figure 7 shows an example of a GPS setup using one of the new modern monuments that we propose to install. Like the existing USGS markers, the small low-impact campaign markers that we install are intended to be permanent. They would become a valuable part of the national surveying infrastructure. As we describe in the next section (Phase 2), our goal is to perform annual surveys using these markers, deploying equipment from July to October each year pending funding.

Figure 7. A typical, stable GPS setup at Sasso della Montesca, near Bologna, Italy, consisting of a GPS antenna (white disk) mounted on a modern GPS monument, a GPS receiver (contained in yellow box covered by plastic bag), and a small battery (next to the yellow box also in the plastic bag). The set ups that we propose for Olympic National Park will be identical to this one, except that we will utilize small portable solar panels and will make an attempt to camouflage all components of the system that do not require sky visibility.

Phase 2: Annual measurement campaigns

We propose to monitor the motion of the new markers, by performing annual surveys with new Topcon GB1000 GPS units. These units are very small and lightweight, easy to transport by pack, and should not detract appreciably from the natural beauty of the park (Figure 7). The units require only a very small amount of energy, which will be provided by small portable solar panels and a very small battery. The GPS units produce no exhaust or other by-products. Our goal is to deploy equipment from July to October each year from 2005 until 2015, pending funding. Set ups will require a site visit by one or more students and/or a geodetic technician each July. The equipment will be left to operate autonomously from July until October. The equipment will be recovered by one or more students in October. Each deployment will be furnished with a small plaque that describes the scientific experiment to curious park visitors, and provide contact information for more information. Based on our experiences in collecting geodetic data in other national parks (Joshua Tree, Death Valley), geodetic observation campaigns typically inspire a great deal of wonder about the natural processes responsible for the parks, and thus have strong potential as an opportunity for education and outreach.

Permits for PBO reference stations

In addition to our main scientific experiment, we also seek permits for the construction of two permanent GPS reference stations within Olympic National Park, one at Hurricane Ridge Visitor Center, and the other located near the Dosewallips Ranger Station. These stations would form part of the new, national GPS infrastructure called the Plate Boundary Observatory or PBO. PBO is a major component of a National Science Foundation Program called Earthscope (cf. http://earthscope.org), which will revolutionize our understanding of the tectonic evolution of the North America continent. These stations would thus contribute to numerous scientific investigations covering a broad range of topics related to the geology and seismic hazards of the western United States.

With regard to our proposed GPS experiment, the Hurricane Ridge and Dosewallips reference stations would allow us to tie our local GPS surveys within the Park to the broader continental-scale PBO network, which will improve our ability to reference motions in Olympic National Park relative to the continental interior of North America. Installation of a continuous GPS reference station involves constructing a shallow-braced monument. This installation consists basically of drilling ~2 m deep holes, which will hold grouted steel rods (Figure 8). Installation requires little more than a moderate-sized drill and appropriate drill bits. Figure 9 shows typical PBO-style GPS stations at Joshua Tree National Park and Mount Olympus.

Figure 8. UNAVCO engineers in the process of installing a continuous GPS reference station. Four holes of 2 meter depth are required. Installation takes rough a few hours.

d. Intended use of results

All data collected would be made available to the general public on an as-soon-as-possible basis through the well-established UNAVCO GPS Data Archive (cf., http://unavco.org/). These data would also contribute to NSF's Earthscope Science program, of which the PBO is a major infrastructural component. We will analyze all satellite data at University of Arizona, using standard geodetic processing software. We expect that the data we collect will form the basis for Ph.D. theses at University of Arizona, Yale University, University of Washington, and elsewhere. We also anticipate that these data would provide scientific results that will be of great interest to park visitors.

The deformation results that we determine from the GPS data will be compared with the geological inferences of Brandon et al. (1998) and Pazzaglia and Brandon (2001). We will test the models of Figures 1B and 3. Furthermore, the results will allow us to estimate the deformation associated with the earthquake process, which is important for improving our estimates of seismic hazards in the Olympics and Puget Sound. Remember that the last rupture of the Cascadia subduction zone occurred in 1700 A.D. (Satake et al. 1996), so we have no direct information about the magnitude of a subduction zone earthquake at the Cascadia margin. Given the regularity of silent events on the Cascadia subduction zone, we will dedicate a significant amount of analysis toward the implications of our results for the dynamics of the subduction zone. We intend to report all of our findings in peer-reviewed journals.

Figure 9. Photographs of continuous GPS stations located at Keys View in Joshua Tree National Park (top) and Mount Olympus in Olympic National Park (bottom). The stations consist of an antenna (grey dome) anchored to the Earth's surface by four braced rods, an equipment enclosure that contains communications equipment and the GPS receiver, and a solar panel array. Continuous reference stations such as these provide the ability to tie local geodetic results to a stable reference frame, considerably increasing the accuracy of local GPS surveys, as well as important information about how the Olympics move with respect to the North America interior.

III. OBJECTIVES/HYPOTHESES TO BE TESTED

As described above, we seek to determine the relative contributions of earthquake cycle effects (Figure 3) and mountain building processes (Figure 1B). Our results will provide a new test the accretionary flux models of Brandon et al. (1998) and Pazzaglia and Brandon (2001) (Figure 1B), by revealing motions on time-scales of < 10 years. Our experiment will provide valuable new constraints on Cascadia's silent earthquakes, which nucleate beneath Olympic National Park. We will also refine estimates for seismic hazard associated with the locked part of the Cascadia subduction interface, which is presently thought to be capable of producing magnitude 9 earthquakes (larger than any earthquake in the written history).

IV. METHODS

a. Description of study area

As we described above, we propose to perform a GPS experiment within the central massif of the Olympic Mountains. Specifically we propose to monitor motion of seven markers within the National Park: Blue Mountain, Cameron Glacier Cirque, Mount Dana, Dodger Point, Eagle Peak, Gray Wolf Ridge, and Mount Carrie.

We also request permission to construct continuous GPS reference stations at Hurricane Ridge Visitor Center and in the vicinity of Dosewallips Ranger Station. These stations would be located in the direct vicinity of Ranger stations.

b. Procedures

Our GPS experiment will follow standard surveying procedures. Passive GPS equipment will be used to record navigation data that is broadcast by the Global Positioning System satellites. We propose to record these data each year during the period of July to October. These navigation data will be used to determine the precise locations of the markers and monitor their motions through time.

The continuous reference stations at Hurricane Ridge Visitor Center and Dosewallips Ranger Station will record navigation signals from satellites continuously throughout the year, tying the Olympic Network to the North America interior.

c. Collections

All data that we collect will be archived at the UNAVCO GPS Data Archive. These data will form a valuable part of the PBO data set.

d. Analysis

Data analyses will be performed at University of Arizona, using high-precision geodetic quality software.

e. Schedule

For the Olympic campaign network, data collection would take place each year from July to October. Each site will be visited by a survey crew consisting of one or two students two times per year; once in July to deploy the GPS equipment, and once in October to recover the equipment.

The continuous reference stations will be constructed as part of the PBO network. The schedule for their deployment would depend on the PBO deployment schedules as determined by PBO Headquarters. We anticipate that the continuous reference station will remain in place for the duration of the Earthscope program, which is expected to last for at least 10 years.

f. Budget

Funding to support our experiment will be requested from the National Science Foundation's Earthscope Science Program. The Earthscope Program announcement is available from <http://www.geo.nsf.gov/cgi-bin/geo/showprog.pl?id=121&div=ear>.

V. PRODUCTS

a. Publications and reports

We intend to publish all scientific results in peer-reviewed journals.

b. Collections

All data products associated with this research will form part of the PBO data set, and will be archived and made freely available through the Internet.

c. Data and other materials

All raw GPS data collect will form part of the PBO data set, and will be archived and made freely available through the Internet.

VI. LITERATURE CITED

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Thatcher, W., Silent slip on the Cascadia subduction interface, *Science, 292*, 1495-1496, 2001.

VII. QUALIFICATIONS

Biographies for Bennett and Brandon are located at the end of the proposal.

VIII. SUPPORTING DOCUMENTATION AND SPECIAL CONCERNS

a. Safety

We foresee no major safety concerns for the researchers who participate in our experiment, for park visitors, nor for animals within the park.

b. Access to study site

Our experiment should not require any special access. All sites are openly accessible by road or trail. To the extent possible, our GPS instruments will be located out of view of park visitors.

c. Use of mechanized and other equipment

Site installation will require the use of a moderate sized drill one time only per site. Installations of campaign markers will take approximately 30 minutes, and installation of continuous GPS reference stations will take approximately 3 hours.

d. Chemical use

Campaign markers and continuous GPS monuments will be attached to the ground using environmentally safe epoxy. Epoxy will be used to fill drill holes, but no epoxy will be exposed to the surface.

e. Ground disturbance

Each campaign marker will require a small hole, 100 cm deep and 3 cm diameter into which the marker will be set. Each continuous site would require 4 holes each, of 2 meters depth and approximately 5 cm diameter.

f. Animal welfare

Animals should be totally unaffected by our experiment.

g. NPS assistance

We do not anticipate requiring assistance from the National Park Service for our proposed campaign GPS experiment.

h. Wilderness "minimum requirement" protocol

Not certain what is required here.

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PRINCIPAL RESEARCH INTERESTS:
Tectonic applications of geodesy; the dynamics of continental fault zones.

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Massachusetts Institute of Technology, Geophysics, Ph.D., 1995
Harvard-Smithsonian Center for Astrophysics, Postdoc, 1996-1998

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2004-present Assistant Professor, Department of Geosciences, University of Arizona
1998-2004 Geodesist, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

AWARDS: 1999, 2000, 2001, 2003: Smithsonian Certificate for Outstanding Achievement
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PROFESSIONAL AFFILIATIONS:
1990-present, American Geophysical Union

PUBLICATIONS
RELEVANT TO PROPOSED RESEARCH:

1) Wernicke, B.P. J.L. Davis, R.A. Bennett, J.E. Normandeau, A.M. Friedrich, N.A. Niemi, Tectonic implications of a dense continuous GPS velocity field at Yucca Mountain, Nevada, Journ. Geophys. Res., in press, 2004.
2) Davis, J. L., R.A. Bennett, B.P. Wernicke, Assessment of GPS velocity accuracy for the Basin and Range Geodetic Network (BARGEN), Geophys. Res. Lett., 30, 10.1029/2003GL016961, 2003.
3) Bennett, R.A., B.P. Wernicke, N.A. Niemi, A.M. Friedrich, and J.L. Davis, Contemporary strain fields in the northern Basin and Range province from GPS data, Tectonics, 22, 1008, doi:10.1029/2001TC001355, 2003.
4) Bennett, R.A., J.L. Davis, B.P. Wernicke, and J.E. Normandeau, Space geodetic measurements of plate boundary deformation in the western U.S. Cordillera, in Plate Boundary Zones, e.d. Stein, S.A., J.T. Freymueller, AGU Geodynamics Series, Vol 30, 27-55, 2002.
5) Bennett, R.A., J.L. Davis, B.P. Wernicke, Present-day pattern of Cordilleran deformation in the western United States, Geology, 27, 371-374, 1999.

OTHER SIGNIFICANT PUBLICATIONS:

1) Bennett, R.A., A.M. Friedrich, K.P. Furlong, Co-dependent histories of the San Andreas and San Jacinto fault zones from inversion of geologic displacement rate data, Geology, 32, 961-964, 2004.

2) Niemi, N.A., B.P. Wernicke, A.M. Friedrich, M. Simons, R.A. Bennett, and J.L. Davis, BARGEN continuous GPS data across the eastern Basin and Range province, and implications for fault system dynamics, Geophys. Journ. Int., in press, 2004.
3) Friedrich, A.M., B.P. Wernicke, N.A. Niemi, R.A. Bennett, and J.L. Davis, Comparison of geodetic and geologic data from the Wasatch region, Utah, and implications for the spectral character of Earth deformation at periods of ten to ten million years, Journ. Geophys. Res., 108, 2199, doi:10.1029/2001JB000682, 2003.
4) Elosegui, P., J.L. Davis, J.X. Mitrovica, R.A. Bennett, and B.P. Wernicke, Crustal loading near Great Salt Lake, Utah, Geophys. Res. Lett., 30, 1111, doi:10.1029/2002GL016579, 2003.
5) Dixon, T., J. Decaix, F. Farina, K. Furlong, R. Malservisi, R.A. Bennett, F. Suarez-Vidal, J. Fletcher, and J. Lee, Seismic cycle and rheological effects on estimation of present-day slip rates for the Agua Blanca and San Miguel-Vallecitos faults, northern Baja California, Mexico, Journ. Geophys. Res., 107, 10.1029/2000JB000099, 2002.

SYNERGISTIC ACTIVITIES:
1) Chair, PBO Site Selection Committee Extension/Intra-plate region, 2003-present.
2) Member, PBO Data Products Advisory Working Group, 2003-present.
3) Member, Stable North America Reference Frame Working Group, 2003-present.
4) Member, Board of Directors, UNAVCO, Inc. 2004-present.

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PROFESSIONAL PREPARATION:
U.C. Santa Cruz, Earth Sciences, B.Sc., 1975
University of Washington, Geological Sciences, M.Sc., 1980; Ph.D., 1984
Pacific Geoscience Centre, Canada, NSERC Postdoctoral Fellowship, LITHOPROBE, 1984-1986

APPOINTMENTS:
2002-present Full Professor without term, Yale University
1996-2001 Associate Professor without term (tenured), Yale University
1991-1996 Associate Professor on term, Yale University
1986-1991 Assistant Professor on term, Yale University, New Haven, Connecticut

HONORS: 1998: Fellow Geological Society of America
2002: GSA Kirk Bryan Award, for paper by Pazzaglia and Brandon (2001, AJS)
2002: M.A. Privatim Degree, Yale University

PROFESSIONAL AFFILIATIONS: Fellow of the Geological Society of America; Member of the American Geophysical Union and International Association of Structural/Tectonic Geologists

PUBLICATIONS (see web site for pdf reprints and full list of publications)
RELEVANT TO PROPOSED RESEARCH:

6) Bernet, M., Zattin, M., Garver, J.I., Brandon, M.T., Vance, J.A., 2001, Steady-state exhumation of the European Alps. Geology, v. 29, no. 1, p. 35-38.
7) Willett, S.D., Brandon, M.T., 2002, On steady states in mountain belts. Geology, v. 30, no. 2, p. 175-178.
8) Bernet, M., Brandon, M.T., Garver, J.I., and Molitor, B., 2004, Downstream changes of Alpine zircon fission-track ages in the Rhône and Rhine rivers. Journal of Sedimentary Research, v. 74, p. 82-94.
9) Bernet, M., Brandon, M.T., Gaver, J.I., Molitor, B.R., 2004, Fundamentals of detrital zircon fission-track analysis for provenance and exhumation studies with examples from the European Alps. In: Geological Society of America Special Paper, "Detrital Thermochronlogy - Exhumation and Landscape Evolution of Mountain Belts", Matthias Bernet and Cornelia Spiegel (editors) in press.
10) Stewart, R.J., Brandon, M.T., 2004, Detrital zircon fission-track ages for the “Hoh Formation”: Implications for late Cenozoic evolution of the Cascadia subduction wedge. Geological Society of America Bulletin, v. 116, p. 60-75

OTHER SIGNIFICANT PUBLICATIONS:

6) Brandon, M.T., Roden-Tice, M.K., and Garver, J.I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, NW Washington State. Geological Society of America Bulletin, v. 110, no. 8, p. 985-1009.
7) Ring, U., Brandon, M.T., Willett, S., and Lister, G., 1999, Exhumation processes, *in* Ring, U., Brandon, M.T., Willett, S., and Lister, G. (editors), Exhumation Processes: Normal Faulting, Ductile Flow, and Erosion, Geological Society of London Special Publication 154, p. 1-27.
8) Pazzaglia, F.J., Brandon, M.T., 2001, A fluvial record of long-term steady-state uplift and erosion across the Cascadia Forearc High, Western Washington State. American Journal of Science, v. 301, p. 385–431.
9) Tomkin, J.H., Brandon, M.T., Pazzaglia, F.J., Barbour, J.R., Willett, S.D., 2003, Quantitative testing of bedrock incision models, Clearwater River, NW Washington State, Journal of Geophysical Research, v. 108, no. B6, 2308, doi:10.1029/2001JB000862.
10) Brandon, M.T., 2004, The Cascadia subduction wedge: the role of accretion, uplift, and erosion. in "Earth Structure, An Introduction to Structural Geology and Tectonics", by B.A. van der Pluijm and S. Marshak, Second Edition, WCB/McGraw Hill Press, p. 566-574

SYNERGISTIC ACTIVITIES:

5) Co-convener of Penrose Conference on “Exhumation Processes: Normal Faulting, Ductile Flow, and Erosion”, Island of Crete, October, 1996
6) Co-Editor, Geological Society of London Special Publication *‘Exhumation Processes: Normal Faulting, Ductile Flow, and Erosion’*, published in August, 1999
7) Co-convener for Penrose Conference on “Tectonics, Climate and Landscape Evolution” in January, 2003, Taiwan. Co-editor for conference volume.
8) NSF Committee, New Departures in Structural Geology, 2002-2003
9) GeoEd Advisory Committee, 2003. Study of teaching methods in structural geology.

EDITORIAL CONTRIBUTIONS:

1) Editorial board for Geology, 1987-1989, 1993-1995, 1999-2001
2) Associate Editor, Geological Society of America Bulletin, 1996-1998, 1999-2001
3) Associate Editor, American Journal of Science, 1995-present

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Graduate (10 total): Last five years: Jessica Graybill (M.Sc.2000), Matthias Bernet (Ph.D. 2002, now Post-Doc U. Pierre Fourier, Grenoble), Jeff Rahl (6^{nd} year grad); James Stevenson (4^{rd} yr grad), Ian Miller (4^{rd} yr grad)
Post-doctors (9 total): Last five years: Meinert Rahn (1997-8, faculty, U. Freiburg), Geoff Batt (1997-2000; faculty, Royal Hollaway), Jonathan Tomkin (2000-2002; faculty, LSU), Jeremy Hourigan (2003-present), Stuart Thomson (2003-present), Nicole Gasparini (2003-present)

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